Fig. 1a

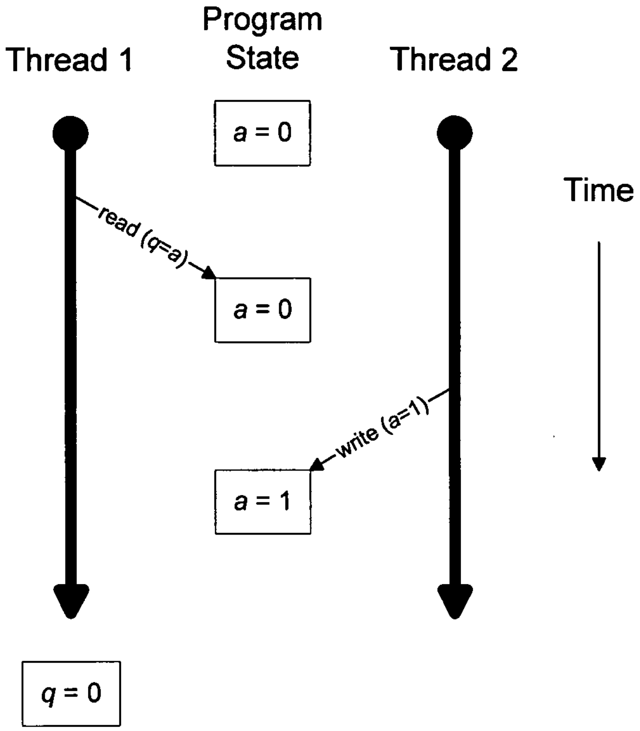

Thread 1
Program State
Thread 2
a = 0
Time
read (q=a)
a = 0
write (a=1)
a = 1
q = 0

Fig. 1b

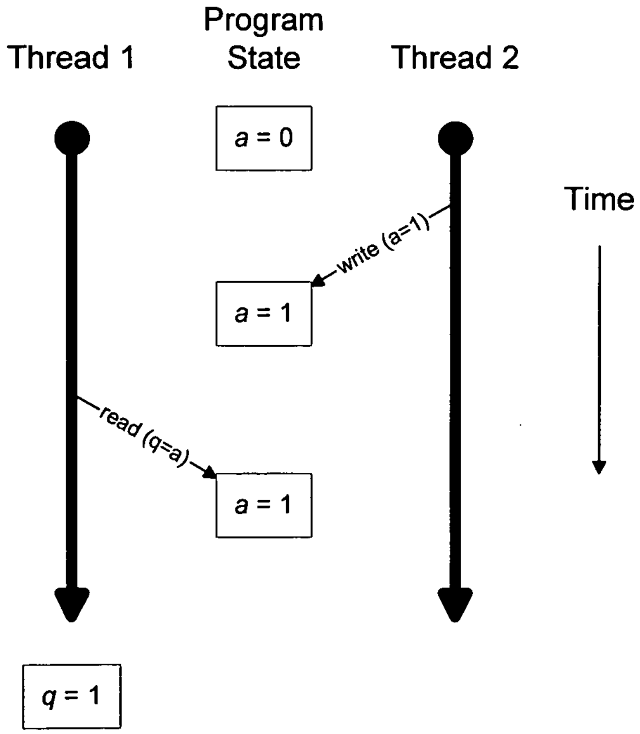

Thread 1
Program State
Thread 2
a = 0
Time
write (a=1)
a = 1
read (q=a)
a = 1
q = 1

Fig. 1c

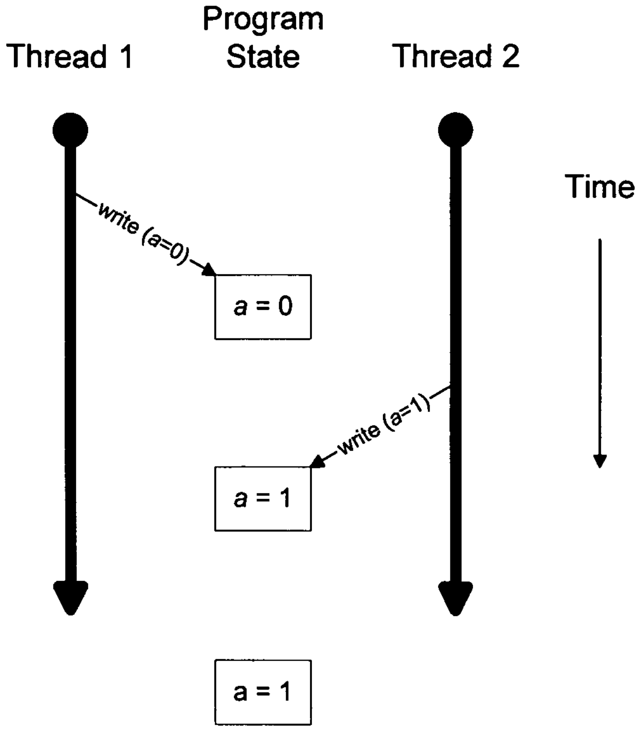

Program State
Thread 1
Thread 2
Time
write (a=0)
a = 0
write (a=1)
a = 1
a = 1

Fig. 1d

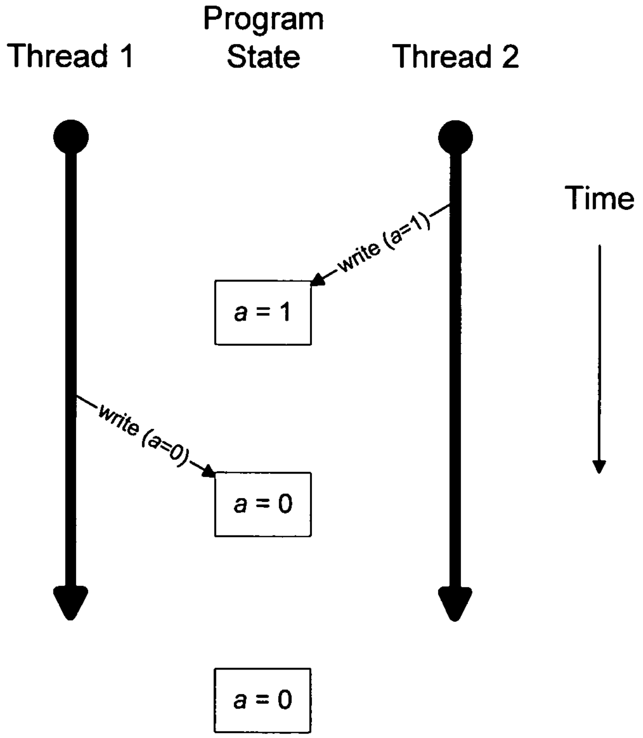

Program State
Thread 1
Thread 2
Time
write (a=1)
a = 1
write (a=0)
a = 0
a = 0

Fig. 2

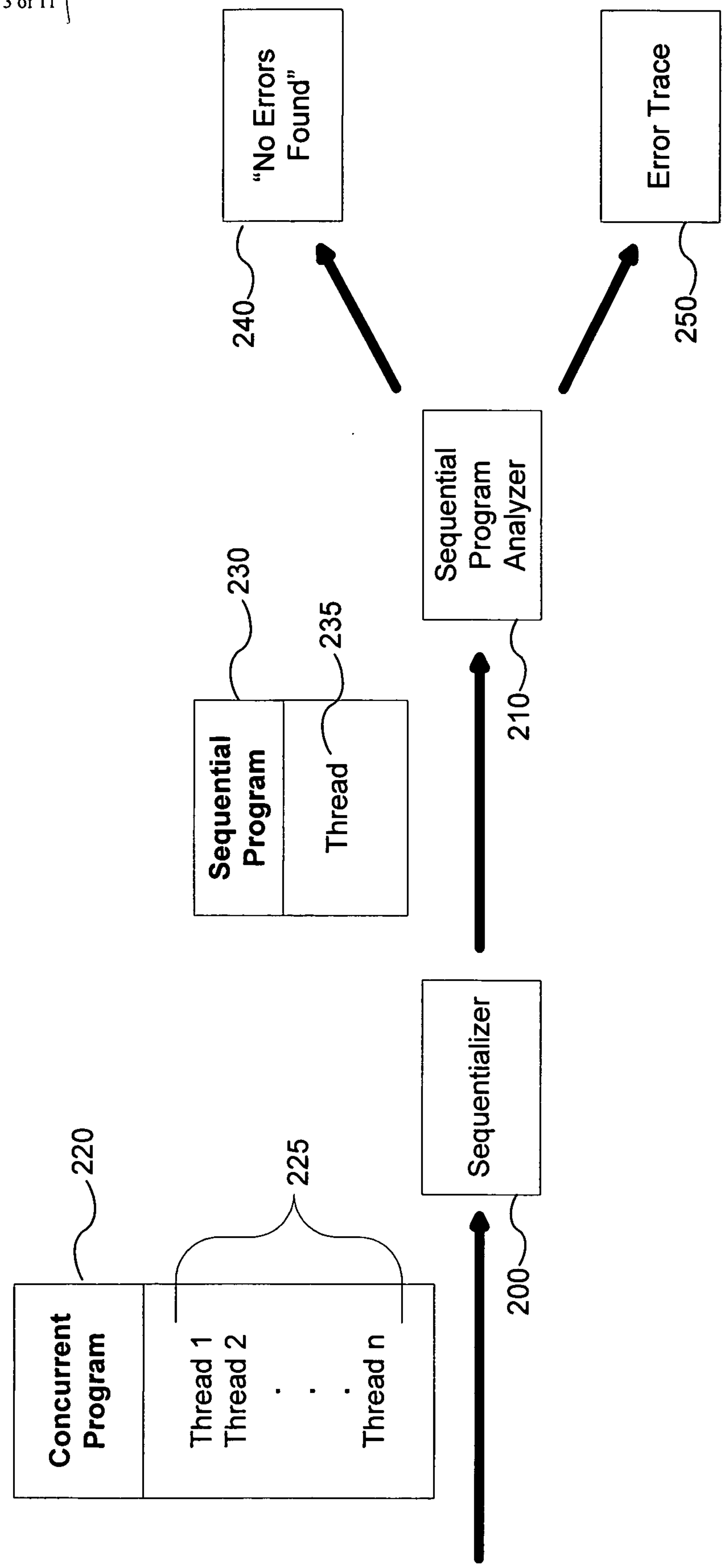

Concurrent Program
Thread 1
Thread 2
. . .
Thread n
220
225
Sequentializer
200
Sequential Program
Thread
230
235
Sequential Program Analyzer
210
"No Errors Found"
240
Error Trace
250

Fig. 3

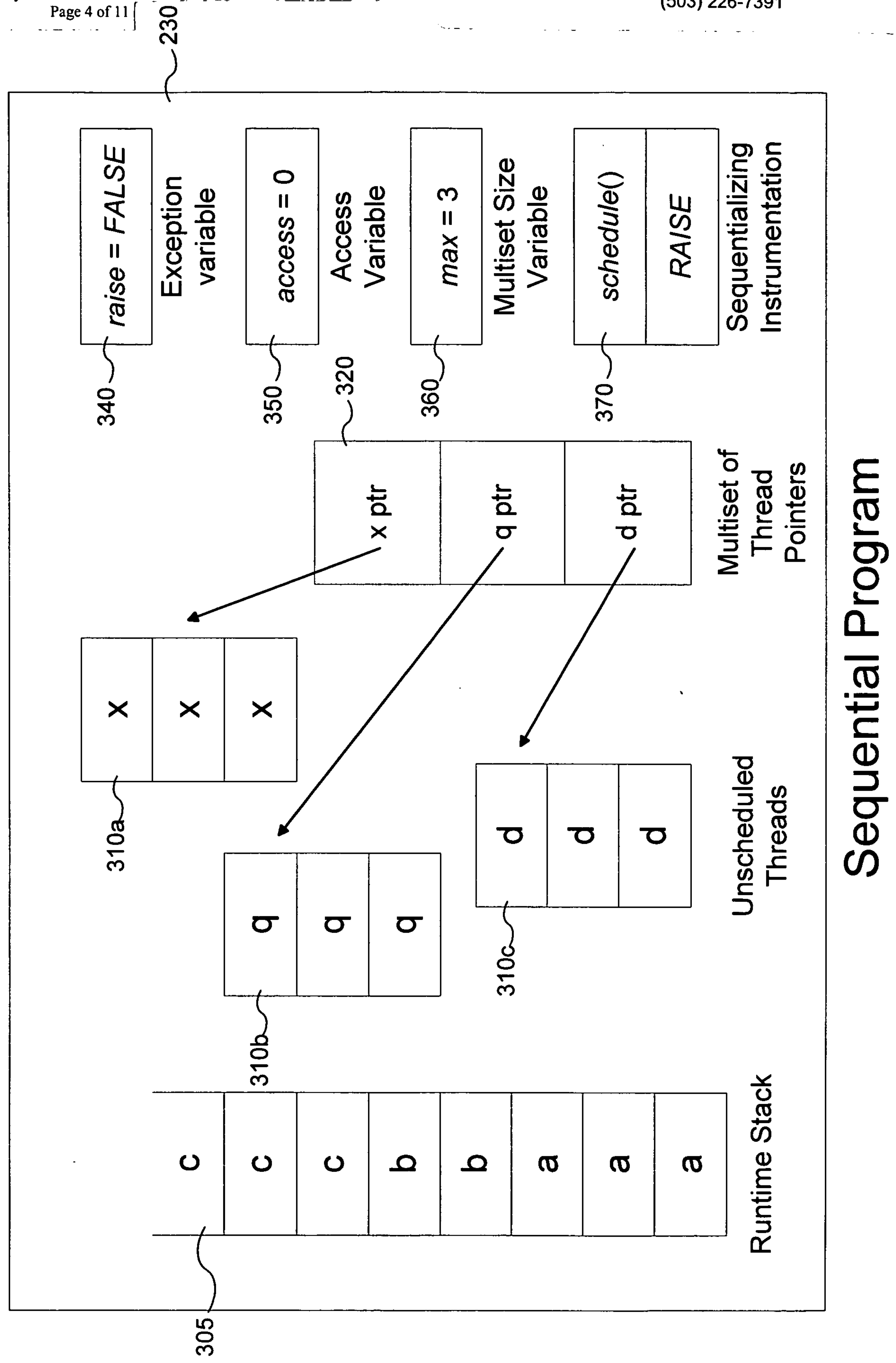

230
raise = FALSE
Exception variable
340
access = 0
Access Variable
350
max = 3
Multiset Size Variable
360
schedule()
RAISE
Sequentializing Instrumentation
370
320
x ptr
q ptr
d ptr
Multiset of Thread Pointers
x
x
x
310a
q
q
q
310b
d
d
d
310c
Unscheduled Threads
c
c
c
b
b
a
a
a
Runtime Stack
305
Sequential Program

Fig. 4

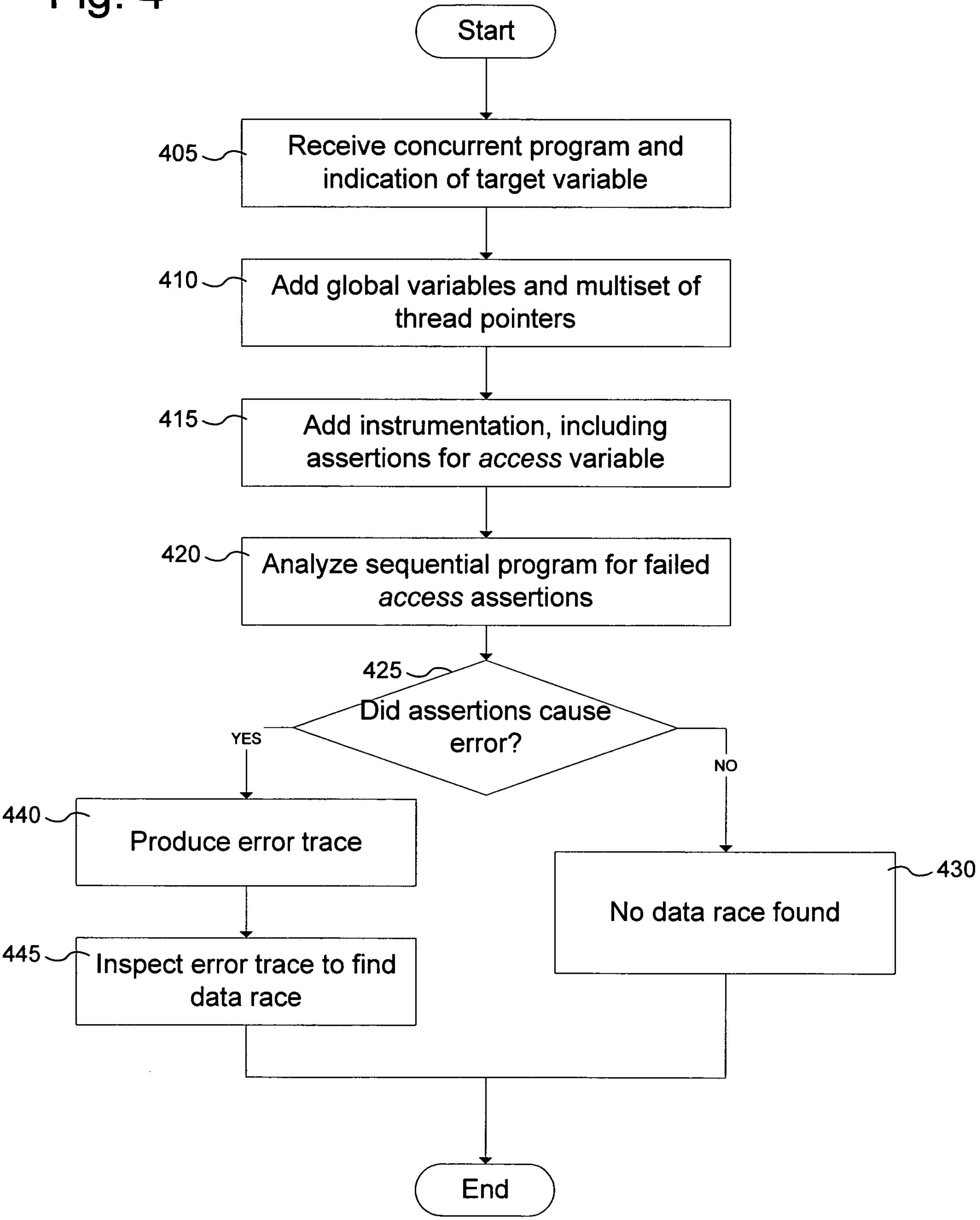

Start
405
Receive concurrent program and indication of target variable
410
Add global variables and multiset of thread pointers
415
Add instrumentation, including assertions for *access* variable
420
Analyze sequential program for failed *access* assertions
425
Did assertions cause error?
YES
NO
440
Produce error trace
445
Inspect error trace to find data race
430
No data race found
End

Fig. 5

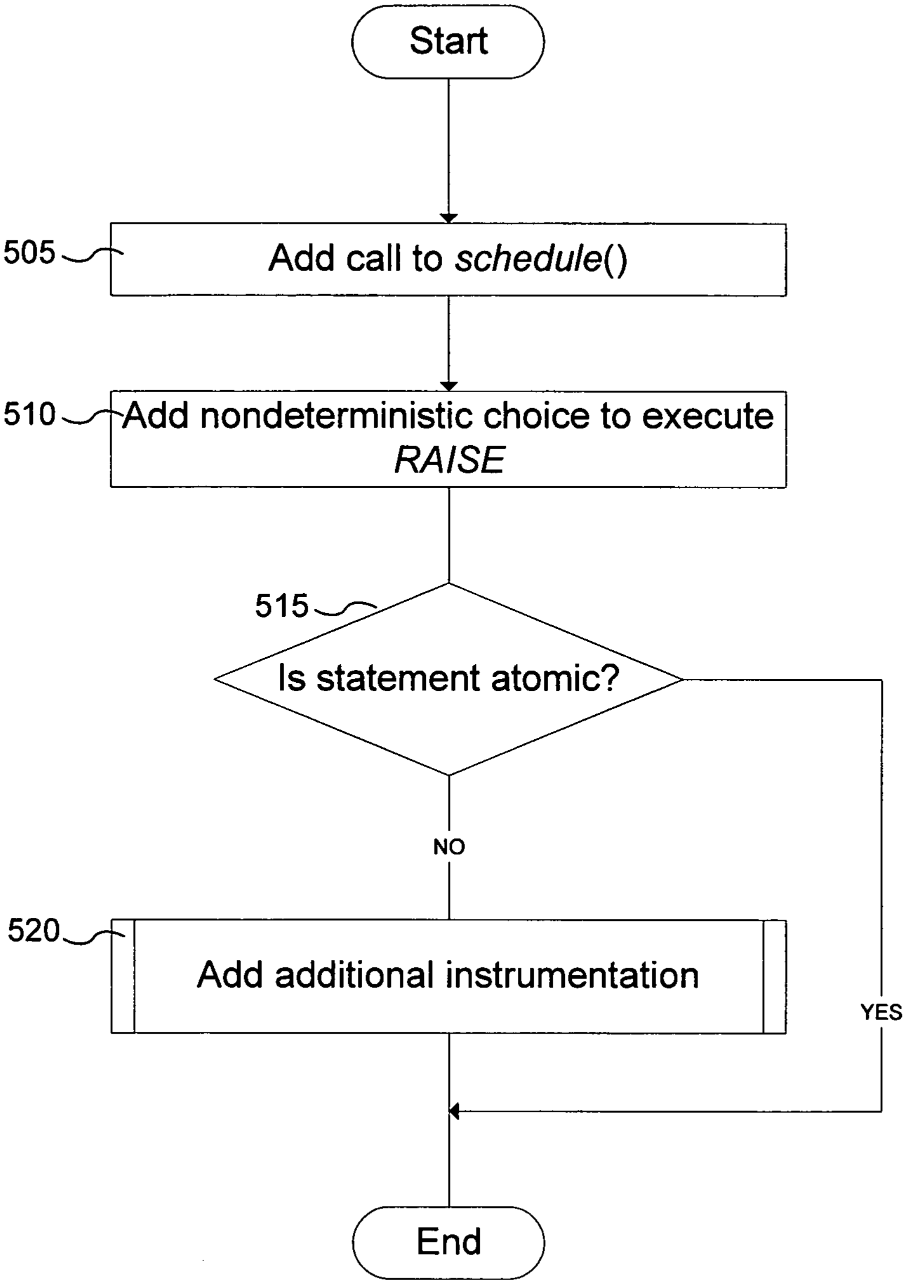

Start
505
Add call to *schedule*()
510
Add nondeterministic choice to execute *RAISE*
515
Is statement atomic?
NO
YES
520
Add additional instrumentation
End

Fig. 6

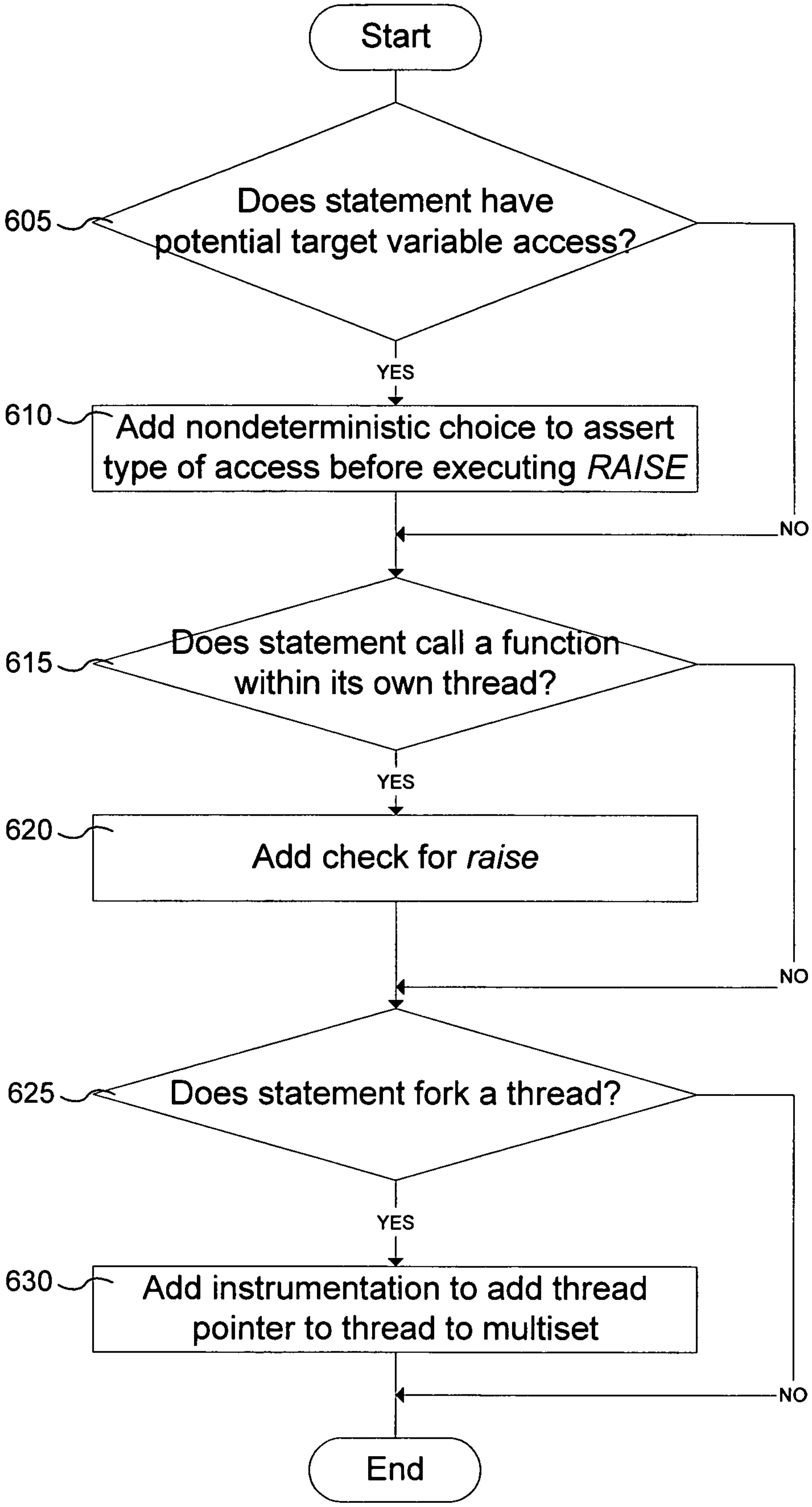

Start
605
Does statement have potential target variable access?
YES
NO
610
Add nondeterministic choice to assert type of access before executing *RAISE*
615
Does statement call a function within its own thread?
YES
NO
620
Add check for *raise*
625
Does statement fork a thread?
YES
NO
630
Add instrumentation to add thread pointer to thread to multiset
End

Fig. 7

| | Original Statement | | Instrumented Sequential Code |
|---|---|---|---|
| 705 | *v* = *c* | = | *schedule*(); *choice*{*skip* [] *check*$_w$(&*v*); *RAISE*}; *v* = *c* |
| 710 | *v* = &$v_1$ | = | *schedule*(); *choice*{*skip* [] *check*$_w$(&*v*); *RAISE*}; *v* = &$v_1$ |
| 715 | *v* = *$v_1$ | = | *schedule*();<br>*choice*{*skip* [] *check*$_r$(&$v_1$); *RAISE* [] *check*$_r$($v_1$); *RAISE* [] *check*$_w$(&*v*); *RAISE*};<br>*v* = *$v_1$ |
| 720 | **v* = $v_1$ | = | *schedule*();<br>*choice*{*skip* [] *check*$_r$(&$v_1$); *RAISE* [] *check*$_r$(&*v*); *RAISE* [] *check*$_w$(*v*); *RAISE*}; **v* = $v_1$ |
| 725 | *v* = $v_1$ op $v_2$ | = | *schedule*();<br>*choice*{*skip* [] *check*$_r$(&$v_1$); *RAISE* [] *check*$_r$(&$v_2$); *RAISE* [] *check*$_w$(&*v*); *RAISE*};<br>*v* = $v_1$ op $v_2$ |
| 730 | *atomic* {*s*} | = | *schedule*(); *choice*{*skip* [] *RAISE*}; *s* |
| 735 | *v* = $v_0$() | = | *schedule*();<br>*choice*{*skip* [] *check*$_r$(&$v_0$); *RAISE* [] *check*$_w$(&*v*); *RAISE*};<br>*v* = $v_0$();<br>*if* (*raise*) *return* |
| 740 | *async* $v_0$() | = | *schedule*();<br>*choice*{*skip* [] *check*$_r$(&$v_0$); *RAISE*};<br>*if* (*size*() < *max*) *put*($v_0$);<br>*else* {$v_0$(); *raise* = *FALSE*} |
| 745 | *return* | = | *schedule*(); *return* |

Code Instrumentation Examples

Fig. 8a

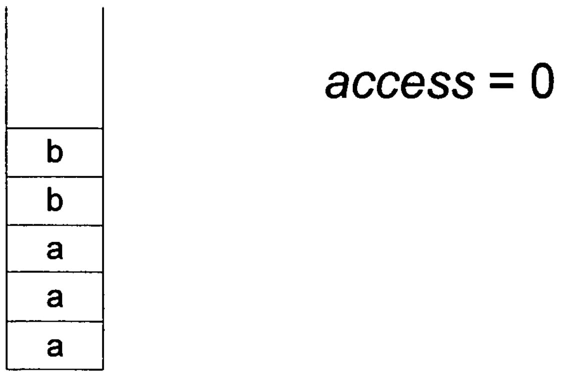


Fig. 8b

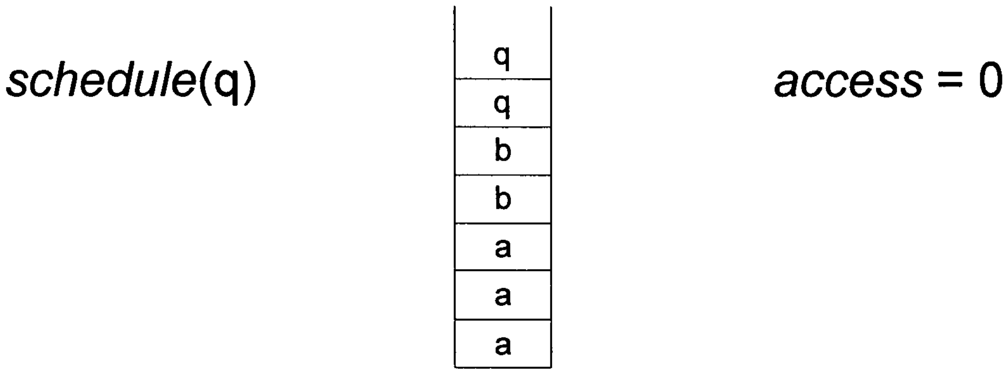


Fig. 8c

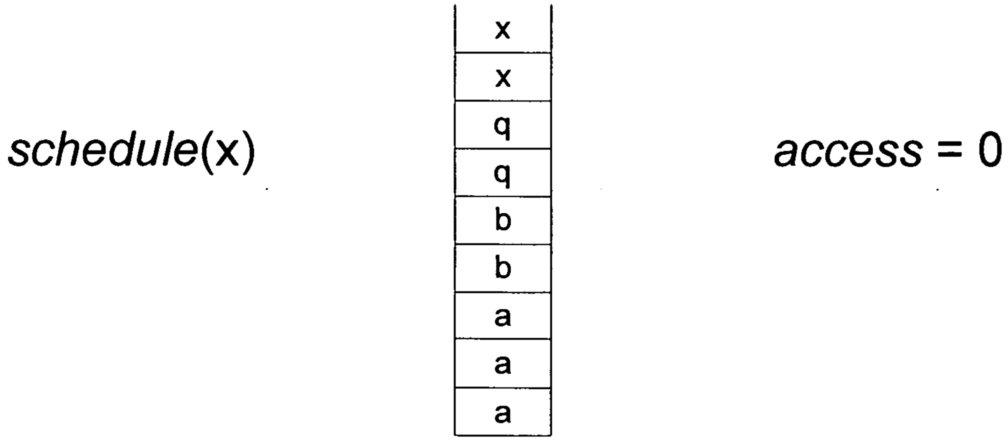


Fig. 8d

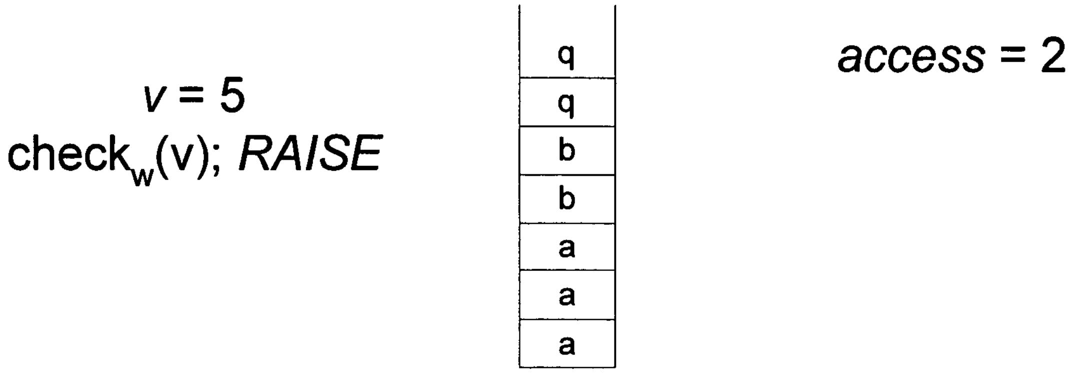


Fig. 8e

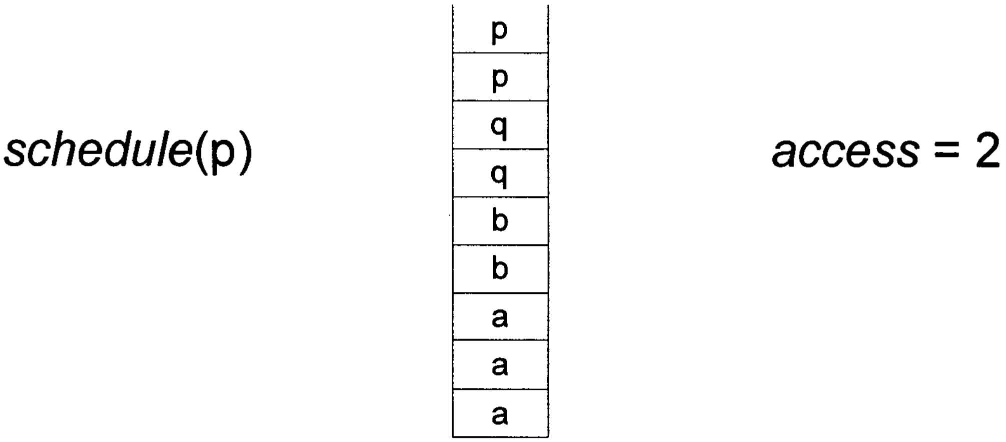


Fig. 8f

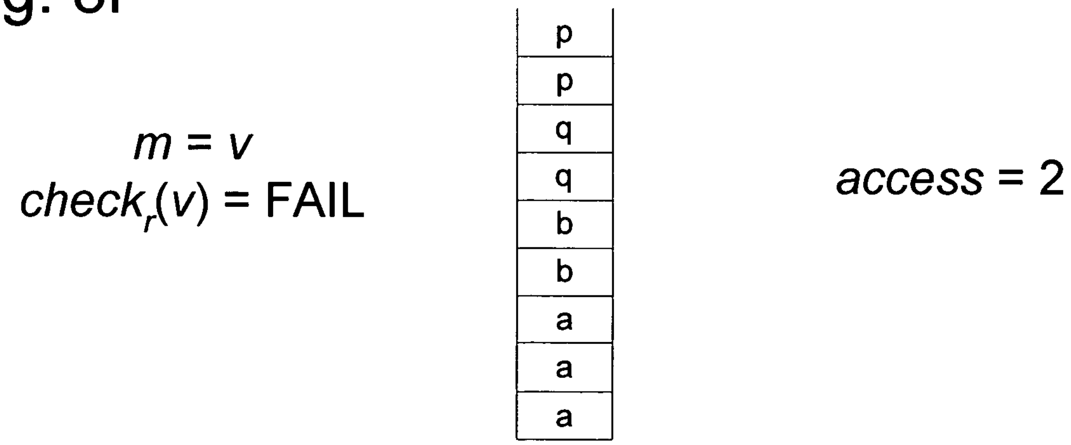
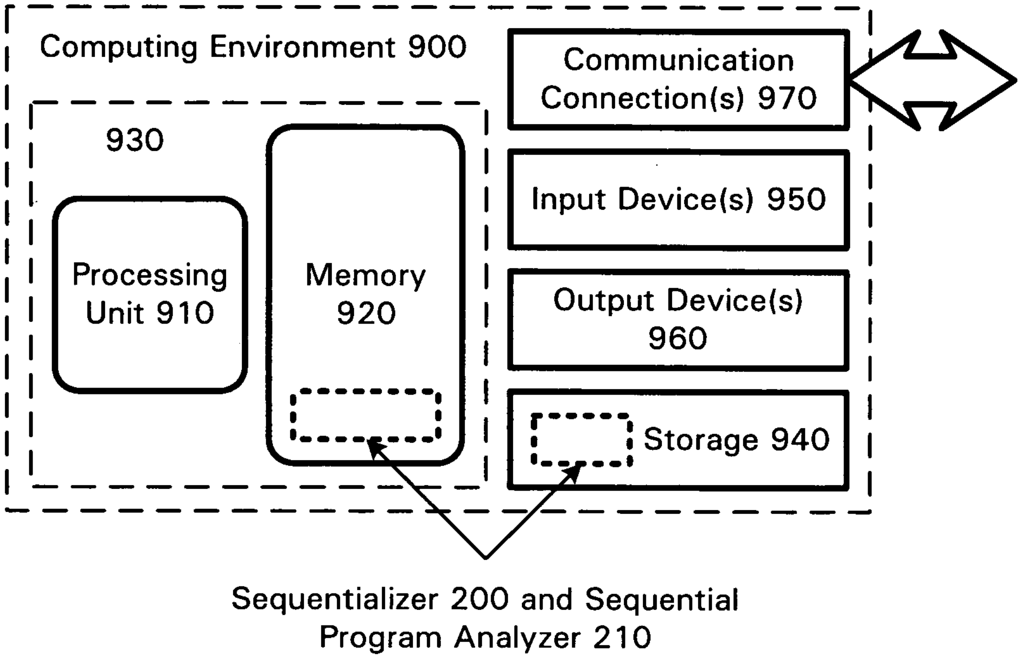


Fig. 9


Computing Environment 900
930
Processing Unit 910
Memory 920
Communication Connection(s) 970
Input Device(s) 950
Output Device(s) 960
Storage 940
Sequentializer 200 and Sequential Program Analyzer 210